Triakis Corporation

System Design Document

For the

Shuttle Remote Manipulator System

A NASA CI03
SARP Initiative 583
IVV-70 Project

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1 Introduction

This specification has been developed to support a research project funded by the NASA Software Assurance Research Program (SARP) during the fiscal year 2003 Center Initiatives (CI03) effort. A system-level, executable specification (ES) based simulation of the Shuttle Remote Manipulator System (SRMS) has been created from the requirements specified in the System Requirements (SARP-I583-001) and Simulator Requirements (SARP-I583-002) Specifications, and will be used as a vehicle for exploring the concepts described in section 2 of Triakis proposal number TC_G020614.

This document describes the system design developed to implement the SRMS as specified in the System Requirements Specification (SARP-I583-001). A simulator will be created and used to evaluate the extent to which the Triakis concept of Executable Specifications (ES') achieves unambiguous communication of system requirements thereby reducing errors induced by interpretation of ambiguous specifications. It will also be used to evaluate the potential that substituting a detailed executable (DE) hardware simulation running actual embedded software, in place of the ES, has for reducing costs and maintaining test consistency through reuse of unmodified system level tests.

Further, new methods of gathering software metrics through use of the simulator will be sought, explored, and evaluated. The virtual system simulator developed for this project will be used to evaluate other potential benefits that its virtual system integration laboratory (VSIL) environment offers in support of general testability, independent validation & verification (IV&V), reliability, and safety.

The format and content of this specification is designed to follow the System Requirements (SARP-I583-001) Specification from which this specification has been developed. As our project effort progresses, this specification will be updated to reflect changes to the scope and fidelity of system requirements due to an improved understanding of the extent that our virtual SRMS must be developed to support our research goals.

1.1 System purpose

The system specified herein is intended to represent the SRMS in a general sense only. The system requirements laid out in this document will form the basis for creating a virtual system simulator that will be used as a vehicle to facilitate the research goals stated in Triakis proposal number TC_G020614. As such, system components and functions of the real-world SRMS that are not required to support our research goals have been omitted.

While the purpose of the actual SRMS is to facilitate the deployment and retrieval of shuttle payloads as well as extra-vehicular activity missions, the derivative SRMS will not incorporate functioning end-effectors required for these purposes. The specified SRMS will demonstrate limited control and movement capability of the RMA along with simulated cameras and video monitors showing the RMA position.

1.2 System scope

The SRMS approximately models a subset of the system characteristics of the existing NASA space shuttle RMS. Adaptations to the functionality of the actual SRMS have been incorporated to the extent required for the stated research purposes and demonstration of the research results.

1.3 Definitions, acronyms, and abbreviations

AFDX Avionics Full Duplex Switched Ethernet
CCTV Closed-Circuit Television
CI03 Center Initiative for fiscal year 2003

C/W	Caution/Warning
DE	Detailed Executable
ES	Executable Specification
EVA	Extra Vehicular Activity
IV&V	Independent Verification and Validation
N/A	Not Applicable
NASA	National Aeronautics & Space Administration
OSMA	Office of Safety and Mission Assurance
PDRS	Payload Deployment and Retrieval System
RHC	Rotational Hand Controller
RMA	Remote Manipulator Arm
RMS	Remote Manipulator System
RMSC	RMS Computer
RMSCP	RMS Control Panel
SARP	Software Assurance Research Program
SimRS	Simulator Requirements Specification
SRMS	Shuttle Remote Manipulator System
SyDD	System Design Document
SyRS	System Requirements Specification
THC	Translational Hand Controller
VSIL	Virtual System Integration Laboratory

1.4 References

http://spaceflight.nasa.gov/shuttle/reference/index.html	NASA Shuttle Reference web site
http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-deploy	NASA PDRS web page
ISBN 0-345-34181-3	Joels, Kennedy & Larkin; Ballantine books, 1988: The Space Shuttle Operator's Manual (Revised Edition)
SARP-I583-001	System Requirements Specification for the Shuttle Remote Manipulator System
SARP-I583-205	System Test Design Document for the Shuttle Remote Manipulator System
TC_G020614	Triakis proposal to NASA for the SARP (Solicitation No: NRA SARP 0201), 14 June 2002

1.5 SRMS overview

Please refer to the NASA PDRS web page for a more complete description of the real space shuttle SRMS that this system is designed to resemble. The following excerpt is included for quick reference:

> *The payload deployment and retrieval system (PDRS) includes the electromechanical arm that maneuvers a payload from the payload bay of the space shuttle orbiter to its deployment position and then releases it. It can also grapple a free-flying payload, maneuver it to the payload bay of the orbiter and berth it in the orbiter. This arm is referred to as the remote manipulator system (RMS).*
>
> *The shuttle RMS is installed in the payload bay of the orbiter for those missions requiring it. Some payloads carried aboard the orbiter for deployment do not require the RMS.*
> *The RMS is capable of deploying or retrieving payloads weighing up to 65,000 pounds. The RMS can also be used to retrieve, repair and deploy satellites; to provide a mobile extension ladder for extravehicular activity crew members for work stations or foot restraints; and to be used as an inspection aid to allow the flight crew members to view the orbiter's or payload's surfaces through a television camera on the RMS.*

2 General system description

The system designer used the following excerpt from the NASA PDRS web page as a reference source and it is given here to provide a general SRMS description for informational purposes only.

The basic RMS configuration consists of a manipulator arm; an RMS display and control panel, including rotational and translational hand controllers at the orbiter aft flight deck flight crew station; and a manipulator controller interface unit that interfaces with the orbiter computer. Normally, only one RMS is installed during a shuttle mission, on the left longeron of the orbiter payload bay.

The RMS arm is 50 feet 3 inches long, 15 inches in diameter, and has six degrees of freedom. The six joints of the RMS correspond roughly to the joints of the human arm with shoulder yaw and pitch joints; an elbow pitch joint; and wrist pitch, yaw and roll joints. The end effector is the unit at the end of the wrist that actually grabs, or grapples, the payload.

The RMS can only be operated in a zero gravity environment, since the arm dc motors are unable to move the arm's weight under the influence of Earth's gravity. Each of the six joints has an extensive range of motion, allowing the arm to reach across the payload bay, over the crew compartment or to areas on the undersurface of the orbiter. Arm joint travel limits are annunciated to the flight crew arm operator before the actual mechanical hard stop for a joint is reached.

One flight-crew member operates the RMS from the aft flight deck control station, and a second flight-crew member usually assists with television camera operations. This allows the RMS operator to view RMS operations through the aft flight deck payload and overhead windows and through the closed-circuit television monitors at the aft flight deck station.

The orbiter's CCTV aids the flight crew in monitoring PDRS operations. The arm has provisions on the wrist joint for a CCTV camera that can be zoomed, a viewing light on the wrist joint and a CCTV with pan and tilt capability on the elbow of the arm. In addition, four CCTV cameras in the payload bay can be panned, tilted and zoomed. Keel cameras may be provided, depending on the mission payload. The two CCTV monitors at the aft flight deck station can each display any two of the CCTV camera views simultaneously with split screen capability. This shows two views on the same monitor, which allows crew members to work with four different views at once. Crewmembers can also view payload operations through the aft flight station overhead and aft (payload) viewing windows.

The arm has a number of operating modes. Some of these modes are computer-assisted, moving the joints simultaneously as required to put the end point (the point of resolution, such as the tip of the end effector) in the desired location. Other modes move one joint at a time; e.g., single mode uses software assistance and direct and backup hard-wired command paths that bypass the computers.

Four RMS manually augmented modes are used to grapple a payload and maneuver it into or out of the orbiter payload retention fittings. The four manually augmented modes require the RMS operator to use the RMS translational hand controller (THC) and rotational hand controller (RHC) with the computer to augment operations.

The THC and RHC located at the aft flight deck station are used exclusively for RMS operations. The THC is located between the two aft viewing windows. The RHC is located on the left side of the aft flight station below the CCTV monitors. The THC and RHC have only one output channel per axis. Both RMS hand controllers are proportional, which means that the command supplied is linearly proportional to the deflection of the controller.

There are two types of automatic modes that can be used to position the RMS arm: operator-commanded and preprogrammed.

The operator-commanded automatic mode moves the end effector from its present position and orientation to a new one defined by the operator via the keyboard and RMS CRT display. The arm moves in a straight line to the desired position and orientation and then enters the hold mode.

The preprogrammed auto sequences operate in a manner similar to the operator-commanded sequences. Instead of the RMS operator entering the data on the computer via the keyboard and CRT display, the RMS arm is maneuvered according to a command set programmed before the flight, called sequences. Each sequence is an ordered set of points to which the arm will move. Up to 200 points may be preprogrammed into as many as 20 sequences.

The description provided is intended to give a general picture of system functionality upon which our virtual system has been modeled. The features actually implemented and the fidelity of this virtual SRMS representation have been chosen according to what is needed to support our overall research goals.

Unless otherwise indicated, subsequent references to all elements of the SRMS and surrounding systems within this document are to be construed as referring to the virtual system elements within the simulator being developed and not the actual SRMS (in use on the NASA shuttle program) on which the virtual system is based.

3 System performance characteristics

3.1 System context

The SRMS described in the SyRS is designed as a self-contained system with few connections to the virtual shuttle within which it will function. Figure 1 shows a screenshot of the simulated RMA within the virtual shuttle orbiter. Neither the manipulator positioning mechanism nor a functioning end effector will be implemented in this SRMS.

The RMA is attached to the portside cargo door support longeron in the shuttle orbiter cargo bay as depicted in Figure 1. [SyRS: R1]

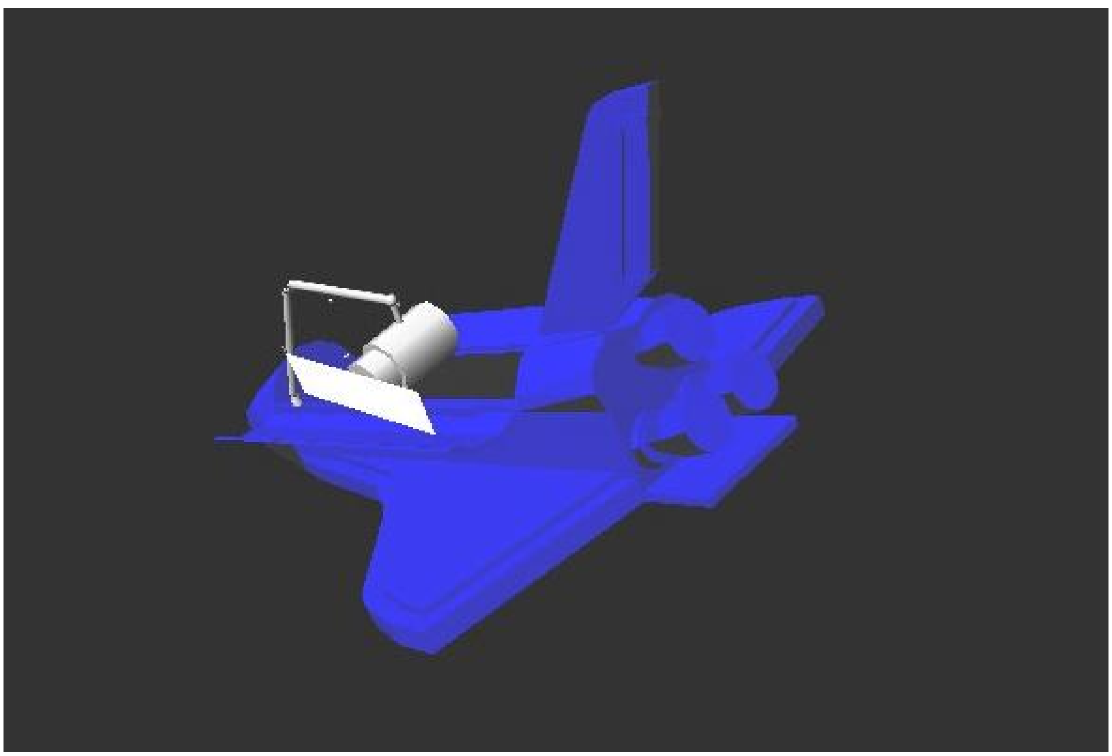

Figure 1: Simulated RMA Within Shuttle Orbiter

The SRMS draws its power from the space shuttle 28VDC and 115VAC/400Hz power supplies as required to function as described herein. [SyRS: R2]

The RMS control & display panel and the closed circuit television (CCTV) monitors that the crew employs in the operation of the SRMS are provided as part of the simulator, but not located on a simulated orbiter flight deck at the aft crew station as originally specified in the SyRS. Instead, the RMS control & display panel will be rendered in a simulator window through which the operator may operate and monitor the SRMS. [SyRS: R3]

3.2 Major system components

The SRMS comprises three principal elements: [SyRS: R4]

a) A remote manipulator arm (RMA) (Figure 1),
b) A RMS control & display panel (Figure 2), and
c) A RMS control computer (RMSCC).

CCTV monitors have been simulated for visually monitoring RMA activity during operation. [SyRS: R5]

The RMSCC provides the interface between the RMS control & display panel and the RMA itself. [SyRS: R6]

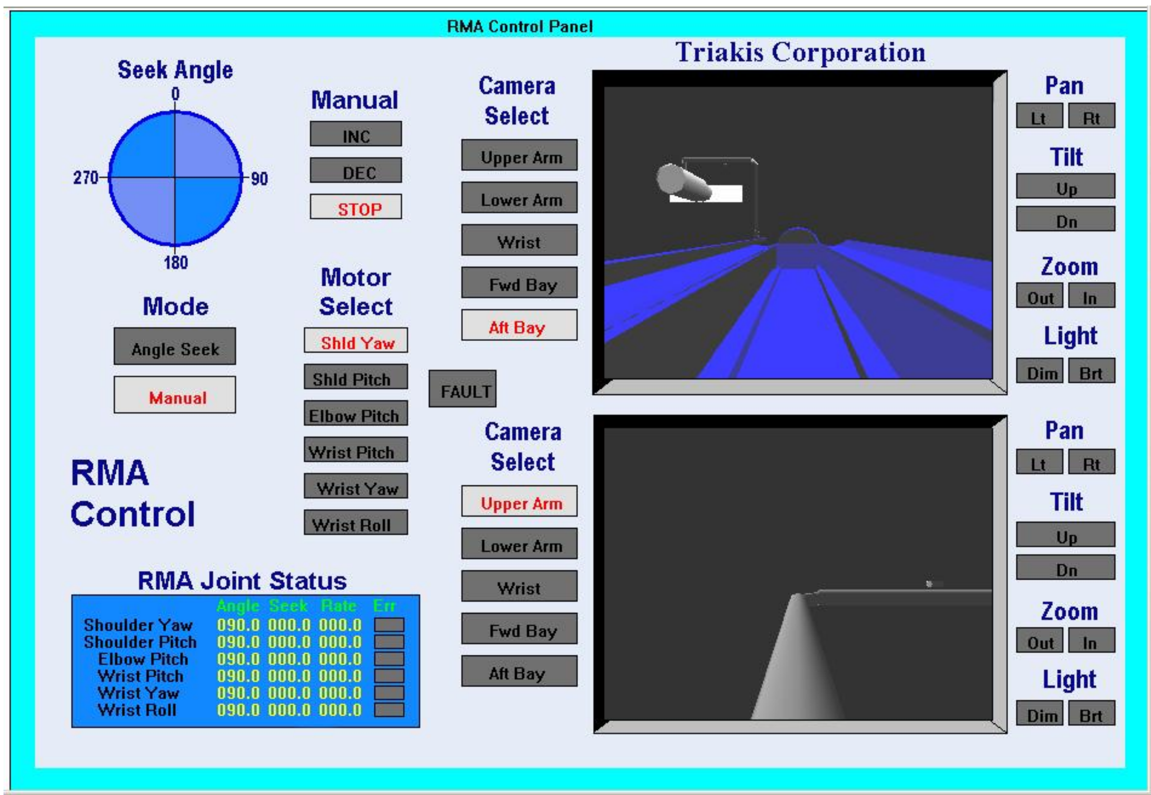

Figure 2: Simulator RMS Control & Display Panel

3.3 System modes and states

The RMS control & display panel, located in the real-world shuttle at the aft crew station, is the primary interface through which the operator controls the RMA. Selection of the operational modes and states is achieved through the RMS control & display panel. The SRMS does not implement all of the functions and modes incorporated in its real-world counterpart, but only the subset described herein.

The SRMS supports two manual operational modes – single-joint control and angle-seek control. [SyRS: R7]

Single-joint manual control allows the operator to move the RMA one joint at a time. [SyRS: R8] The operator may select any one of the six RMA joints to increment/decrement the joint angle, and stop it on command. [SyRS: R9]

Single-joint manual control is selected by clicking on the "Manual" mode button. Control of an RMA joint is managed through the use of the "Motor Select" and "Manual" button groups on the RMS Control Panel shown in Figure 2. After selecting the RMA joint to be moved using the "Motor Select" buttons, the operator then clicks the "INC", "DEC", or "STOP" buttons to move and stop the selected joint. When incrementing, the selected joint angle moves at a rate of 7.2 degrees/sec.

The selected joint will continue moving at a constant rate until the "STOP" button is clicked, at which time the joint will cease moving and hold its position [SyRS: R18]. The selected joint may also be stopped by any of the following actions:

1. Clicking on the lit "INC" or "DEC" button,
2. Selecting a different RMA joint by clicking on its associated button, or
3. Selecting the Angle-Seek mode by clicking on its associated button.

When a joint is in motion, clicking on the unlit "INC" or "DEC" button will cause it to come to a stop and then proceed in the opposite direction at a rate of 7.2 degrees/sec.

Angle-seek mode provides for computer-assisted manual RMA control. [SyRS: R10] The computer control is optimized so that the selected joint travels in the direction of the shortest distance from its present angle to the commanded seek angle. [SyRS: R11]

Angle-Seek mode allows the operator to select a destination angle to which the joint is to be positioned. The operator inputs the desired destination angle by clicking on the corresponding spot on a 360-degree circle graphic located in the upper left corner of the RMS Control Panel. The present joint angle is shown in the RMA Joint Status display along with the seek angle selected. [SyRS: R12]

The computer automatically increments or decrements the selected joint angle at a rate of 7.2 degrees/sec to arrive at the destination angle in the shortest time possible. The operator may stop the selected joint by clicking on the manual "STOP" button [SyRS: R13]. While clicking on the "INC" or "DEC" buttons has no effect, one or the other will light to indicate the direction the joint is moving.

Angle-Seek mode allows the operator to control multiple RMA joints simultaneously. A new joint may be selected and a seek angle may be entered without affecting the progress of the other joints. Each joint will automatically stop upon arrival to within 2.5 degrees of its seek angle. When a joint reaches its destination, the motor select button corresponding to that joint will light and the manual "STOP" button will light. All joints will be immediately stopped and their corresponding seek angles will be set to their current position upon selection of the "manual" mode button [SyRS: R14]. After stopping, the joints will hold their positions until commanded to move. [SyRS: R15, 18]

3.4 Major system capabilities

The RMA is implemented with 6 degrees of freedom corresponding roughly to the joints of the human arm i.e.: shoulder yaw & pitch joints; elbow pitch joint; and wrist pitch, yaw, & roll joints. [SyRS: R16]

Normal RMA braking is accomplished through deceleration of each joint motor. [SyRS: R17]

The RMA dimensions are approximately proportional to those of its real-world counterpart whose 13-inch diameter upper and lower arms have lengths of 17 and 20 feet respectively. [SyRS: R19]

The shuttle 3D orbiter image used establishes the scale size to which the RMA is rendered. [SyRS: R20]

Both the upper and lower RMA booms are equipped with strain gauge sensors to measure the dynamic forces exerted on them during operation. [SyRS: R21]

The SRMS design incorporates five CCTV video cameras as specified in the System Requirements Specification. Each of the cameras is equipped with pan, tilt, and zoom capability in addition to featuring a controllable light source. The cameras are located as stated in the SyRS i.e.:

- One on the RMA upper arm boom, [SyRS: R22]
- One on the RMA lower arm boom, [SyRS: R22]
- One at the RMA wrist joint, [SyRS: R22]
- One at the aft wall of the shuttle bay, and [SyRS: R23]
- One at the forward wall of the shuttle bay. [SyRS: R23]

The RMS Control Panel incorporates two video display monitors and buttons as required for displaying CCTV video from any of the five video cameras. [SyRS: R24]

> To the left of each video monitor on the RMS Control Panel are five buttons used to select the desired camera view for display. Camera controls located to the right of the video display monitors on the RMS Control Panel are used for positioning, and zooming the camera whose view has been selected for display. While buttons have been incorporated into the control panel for controlling the lighting level of the selected camera view, the lamp parts have not been programmed to implement that functionality for this project.

3.5 System design description

Power is supplied to the SRMS from the 115vac main shuttle avionics power bus via a circuit breaker on the Power Control Panel. The RMS Computer converts the incoming power to DC voltages suitable to power its own electronics as well as those within the RMS Control Panel. The Power Contol Panel supplies power to the shuttle bay cameras and the Remote Manipulator Arm as well. Figure 3 contains a block diagram of the Shuttle Remote Manipulator System.

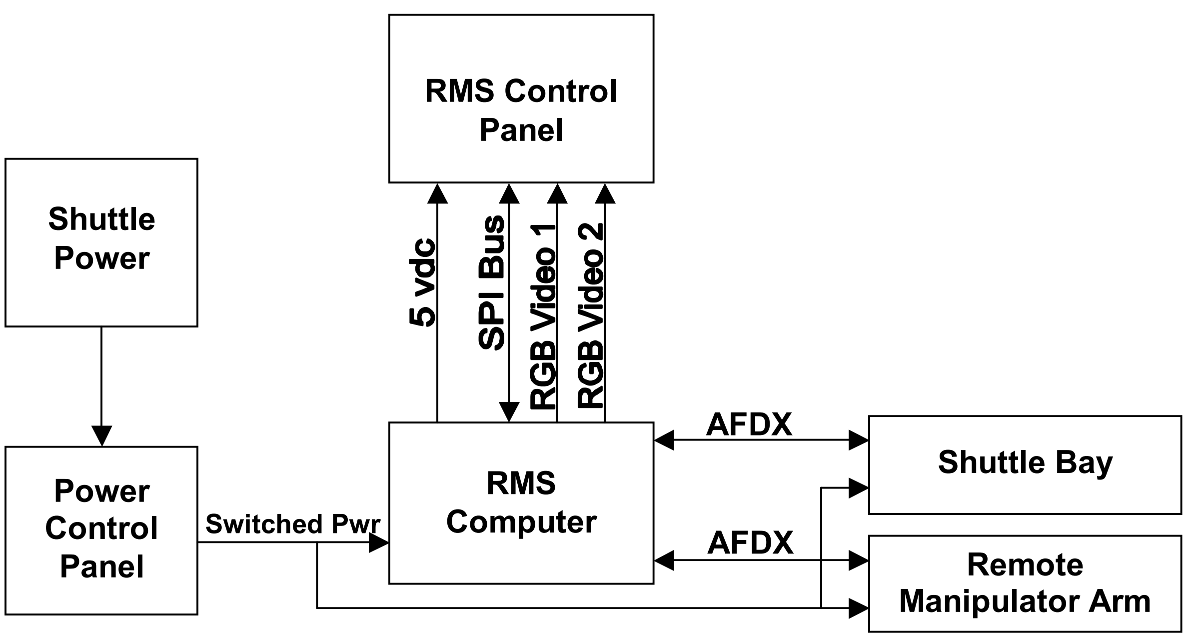

Figure 3: Shuttle RMS Block Diagram

The RMS Computer communicates with the Remote Manipulator Arm and the cameras in the shuttle bay via Avionics Full Duplex Switched Ethernet (AFDX) serial high-speed databuses. In addition to commands and status information, digital compressed video from the CCTV cameras are conveyed over these databuses.

The RMS Computer converts the compressed digital camera video signals into RGB format to drive the video inputs of the two video display monitors located on the RMS Control Panel. The RMS Computer communicates with the RMS Control Panel via the Serial Peripheral Interface bus.

3.5.1 RMS Computer subsystem

The RMS Computer contains the central processor that is programmed to control the entire system in response to commands entered via the RMS Control Panel. A block diagram of the RMS Computer is shown in Figure 4.

The Computer design is based upon the Motorola MPC555, a PowerPC core microcontroller chip. With its high level of integrated functions, the MPC555-based design requires peripheral circuitry only for the AFDX interfaces and to manage the conversion of digital video to RGB video. In addition to the MPC555, the RMS Computer comprises a power converter, an AFDX router, and a digital to RGB converter.

The power converter is responsible for converting the incoming shuttle electrical power into DC power required internally and by RMS Control Panel subsystem. The AFDX router directs communication between the MPC555 and all subsystem elements connected to the AFDX data buses. The Digital to RGB converter receives compressed digital camera video data from the source selected at the control panel and outputs video data in standard RGB format for display on the corresponding control panel video monitor.

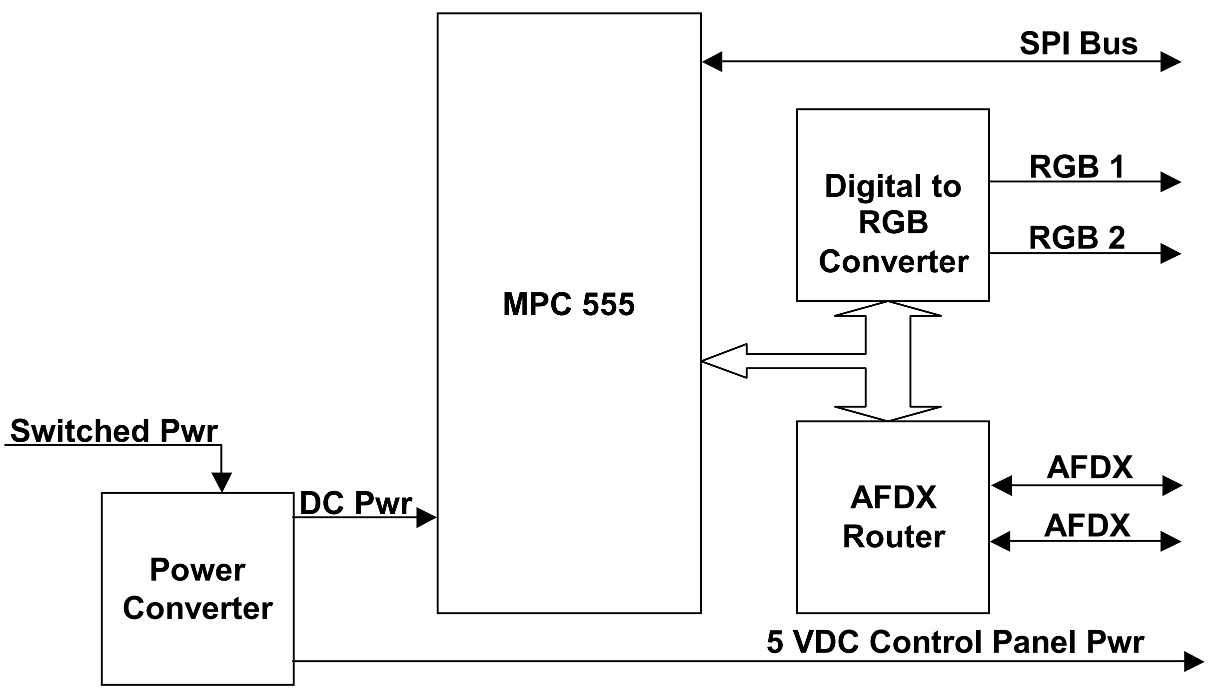

Figure 4: RMS Computer Block Diagram

3.5.2 RMS Control Panel subsystem

The RMS Control Panel is depicted in Figure 2. Refer to paragraphs 3.2, 3.3, 3.4, and 4 for a detailed description of the functionality of the RMS Control Panel.

The RMS Control Panel receives DC power from the RMS Computer and communicates with it via the industry standard SPI bus. All user activated control inputs are passed to the RMS Computer and displayed data & indicators are driven by inputs received from the RMS Computer via the SPI bus. The RMS Computer and the RMS Control Panel may each send data asynchronously to the other. Table 1 lists the message formats used for sending data from the RMS Control Panel to the RMS Computer.

Table 1: RMS Control Panel SPI Bus Output Data Message Formats

Packet ID Data[0]	Data Word No.	Data Definition
0 = Select Mode	Data[1]	0 = Angle Seek command mode 1 = Manual command mode
1 = Select Motor	Data[1]	0 = shoulder yaw motor 1 = shoulder pitch motor 2 = elbow motor 3 = wrist pitch motor 4 = wrist yaw motor 5 = wrist roll motor
2 = Manual Command	Data[1]	0 = Increment 1 = Decrement 2 = Stop 3 = Command Buttons Off
3 = Angle Seek	Data[1]	0 = Shoulder Yaw 1 = Shoulder Pitch 2 = Elbow Pitch 3 = Wrist Pitch 4 = Wrist Yaw 5 = Wrist Roll
	Data[2]	Seek Angle Integer
	Data[3]	Seek Angle Fraction * 4096
4 = Video1 Select	Data[1]	0 = Upper Arm camera 1 = Lower Arm camera 2 = Wrist camera 3 = Forward Bay camera 4 = Aft Bay camera
5 = Video2 Select	Data[1]	0 = Upper Arm camera 1 = Lower Arm camera 2 = Wrist camera 3 = Forward Bay camera 4 = Aft Bay camera
6 = Camera 1 Control	Data[1]	**Camera 1 Control Word (packed bits)** 1 = Pan Left 2 = Pan Right 4 = Tilt Up 8 = Tilt Down 10 = Zoom In 20 = Zoom Out 40 = Light Dim 80 = Light Bright

Packet ID Data[0]	Data Word No.	Data Definition
7 = Camera 2 Control	Data[1]	**Camera 2 Control Word (packed bits)** 1 = Pan Left 2 = Pan Right 4 = Tilt Up 8 = Tilt Down 10 = Zoom In 20 = Zoom Out 40 = Light Dim 80 = Light Bright

Table 2 lists the SPI Bus Packet ID and data sent by the RMS Computer to the RMS Control Panel. The data types shown in the Packet ID column identify the type of data being received. RMS Computer data is used to update the RMA joint status display, control the backlight of the manual control switches, and to light or extinguish the 'Fault' lamp. All data packets consist of 16-bit words sent in the sequence given in Table 2.

Table 2: RMS Computer SPI Bus Data Packet Contents

Packet ID Data[0]	Data Word No.	Data Definition
0 = Panel Display Data	Data[1]	**Display Row (RMA Joint)** 0 = Shoulder Yaw 1 = Shoulder Pitch 2 = Elbow Pitch 3 = Wrist Pitch 4 = Wrist Yaw 5 = Wrist Roll
	Data[2]	Joint Angle Integer
	Data[3]	Joint Angle Fraction * 4096
	Data[4]	Seek Angle Integer
	Data[5]	Seek Angle Fraction * 4096
	Data[6]	Joint Rate Integer
	Data[7]	Joint Rate Fraction * 4096
1 = Manual Command Data	Data[1]	**RMA Joint** 0 = Shoulder Yaw 1 = Shoulder Pitch 2 = Elbow Pitch 3 = Wrist Pitch 4 = Wrist Yaw 5 = Wrist Roll
	Data[2]	0 = Increment 1 = Decrement 2 = Stop 3 = Command Buttons Off

Packet ID Data[0]	Data Word No.	Data Definition
2 = Fault Data	Data[1]	**Fault Data Word (packed bits: 1 = Fault)** 0x 1 = Master Fault 0x 2 = Shoulder Yaw Fault 0x 4 = Shoulder Pitch Fault 0x 8 = Elbow Pitch Fault 0x 10 = Wrist Pitch Fault 0x 20 = Wrist Yaw Fault 0x 40 = Wrist Roll Fault

3.5.3 Shuttle Bay subsystem

In addition to containing the RMA assembly, the shuttle bay contains two video cameras mounted on the fore and aft bay walls (or bulkheads). These cameras are powered from the Power Control Panel. A block diagram of the shuttle bay subsystem is given in Figure 5 below.

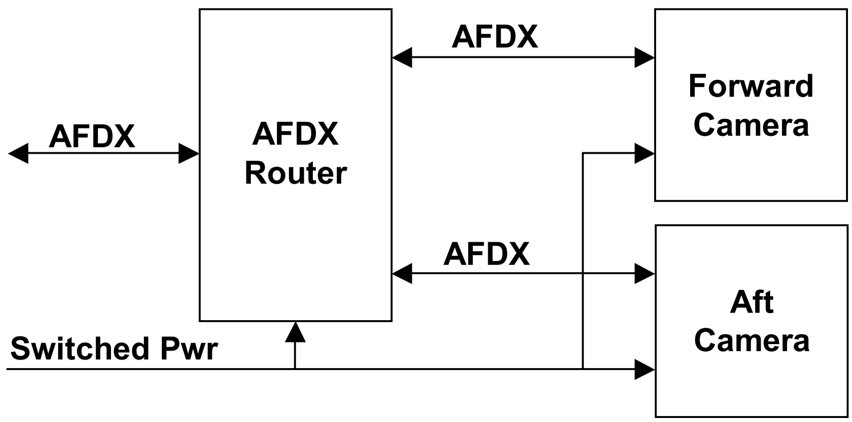

Figure 5: Shuttle Bay Subsystem Block Diagram

All five cameras used in the SRMS are identical comprising yaw, pitch, & zoom control. Video images are digitized, compressed, and transmitted to the RMS Computer via the AFDX data bus. A block diagram of the shuttle bay camera design is given in Figure 6

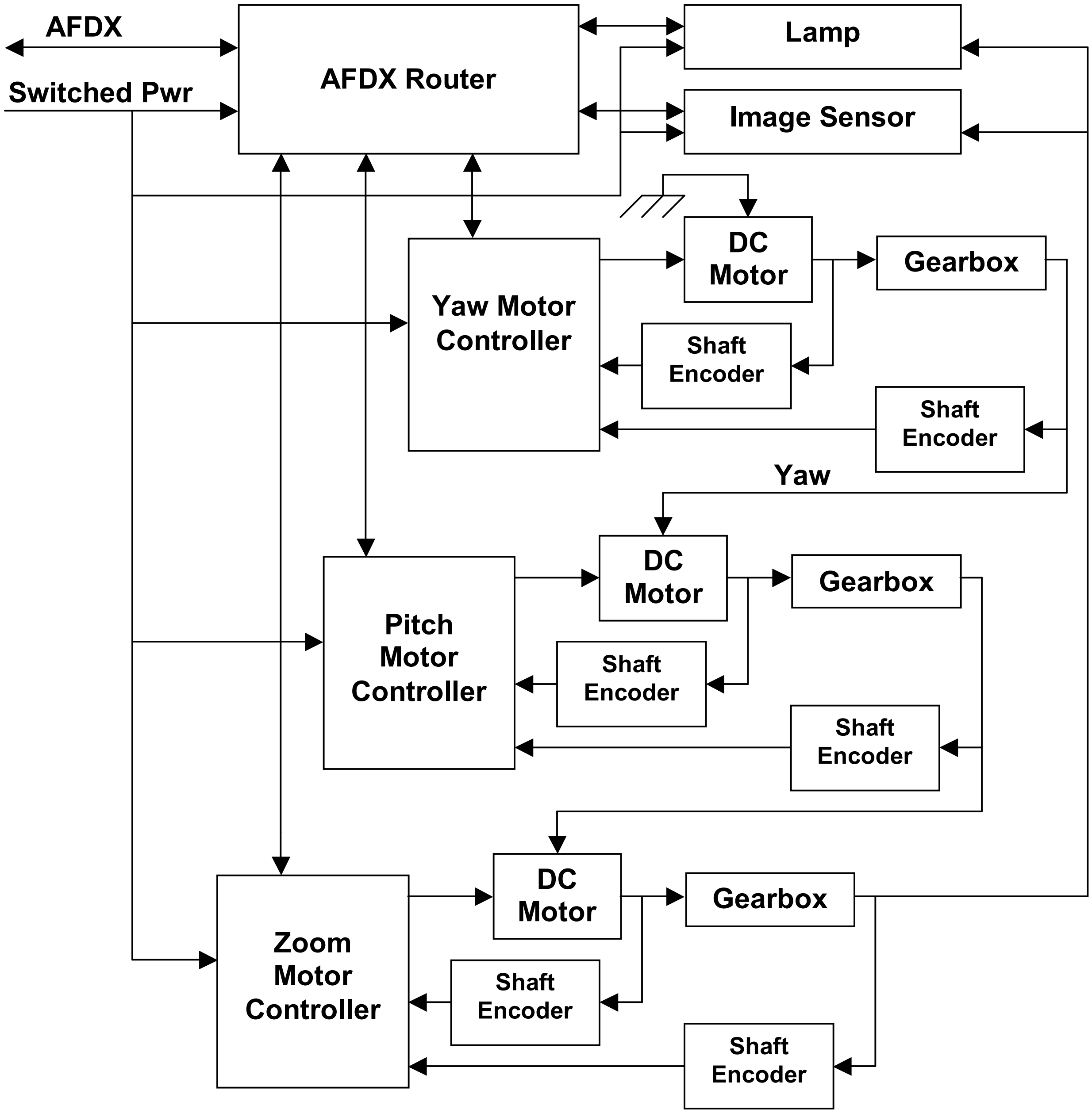

Figure 6: Shuttle Bay Camera Block Diagram

All communications between the RMS Computer and the cameras are accomplished through a single AFDX serial data bus. An AFDX router located in the shuttle bay provides a connection between the single AFDX bus from the RMS Computer and the two cameras. The AFDX address map for the two bay cameras is given in Table 3.

Table 3: Shuttle Bay AFDX Bus Address Map

Address	Receiver
0x141	Forward Bay Camera Pitch Controller
0x142	Forward Bay Camera Yaw Controller
0x143	Forward Bay Camera Zoom Controller
0x144	Forward Bay Camera Lamp
0x145	Forward Bay Camera Image Sensor
0x151	Aft Bay Camera Pitch Controller
0x152	Aft Bay Camera Yaw Controller
0x153	Aft Bay Camera Zoom Controller
0x154	Aft Bay Camera Lamp
0x155	Aft Bay Camera Image Sensor

Each camera has an integrated lamp that can be set to a desired illumination level on command from the RMS Computer. Table 4 gives the AFDX command format for controlling the camera lighting. Lamp intensity is proportional to the data value, with 0 being OFF and 100 being maximum illumination. While the lamp part has been created, the actual lighting ability will not be implemented for this project.

Table 4: AFDX Command for Camera Light Control

Message Type	AFDX Dest. Addx	Src Addx Data[0]	Data Type Data[1]	Data Type Data[2]
3 = Execute Command	Device Addx	0x0000	8 = Illumination	Lamp Intensity (0-100%) (Integer)

Each camera has an integrated image sensor that is responsible for transmitting the current camera view upon command from the RMS Computer. There are three basic message types used by the RMS Computer to communicate with all AFDX devices:

a) **Query Status – All:** Requests the status of all AFDX devices;
b) **Query Response:** Requests data of a specific AFDX device;
c) **Execute Command:** Issues a command for a specific AFDX device to execute.

AFDX messages from the RMS Computer to the Image Sensors take the form shown in Table 5. The Execute Command message is intended for future conceived capabilities.

Table 5: AFDX Commands to the Camera Image Sensor

Message Type	AFDX Dest. Addx	Src Addx Data[0]	Data Type Data[1]
1 = Query Status - All	Unused	0x0000	Unused
2 = Query Response	Device Addx	0x0000	1 = Status
			9 = CamImage
3 = Execute Command	Device Addx	0x0000	2 = Self Test

The Image Sensor sends messages only in response to commands from the RMS Computer. The format of the Image Sensor response messages is shown in Table 6. Responses to the three basic message types used by the camera image sensors to communicate with the RMS Computer are:

a) **Query Status – All:** Sends a 16-bit status word (0x0000 = Healthy);
b) **Query Response:** Sends 320x240x4 byte image bitmap;
c) **Execute Command:** No commands currently supported, acknowledges with sensor status.

Table 6: AFDX Responses from the Camera Image Sensor

Message Type	Dest. Addx	Src. Addx Data[0]	Data Type Data[1]	Status Wd Data[2]	Pointer Flag	Num Bytes	Data Pointer
1 = Query Status - All	0x0000	Device Addx	1 = Status	16-bit status word	FALSE	Unused	Unused
2 = Query Response	0x0000	Device Addx	1 = Status	16-bit status word	FALSE	Unused	Unused
			9 = Camera Image	16-bit status word	TRUE	307,200	Pointer to Image Bitmap
3 = Execute Command	0x0000	Device Addx	1 = Status	16-bit status word	FALSE	Unused	Unused

3.5.4 Remote Manipulator Arm subsystem

The RMA, located in the shuttle bay, is a six degree-of-freedom robotic arm with joint axis mimicking those of the human arm. The RMA receives its power from the Power Control Panel and all communication with the arm is conducted through the AFDX serial data bus.

The RMA comprises six major components mechanically and electrically linked together as shown in the block diagram in Figure 7. Power is daisy-chained from one component to the next. Within each component is an AFDX router that connects controllers and/or cameras within the component, as well as the next component in the link to the AFDX bus.

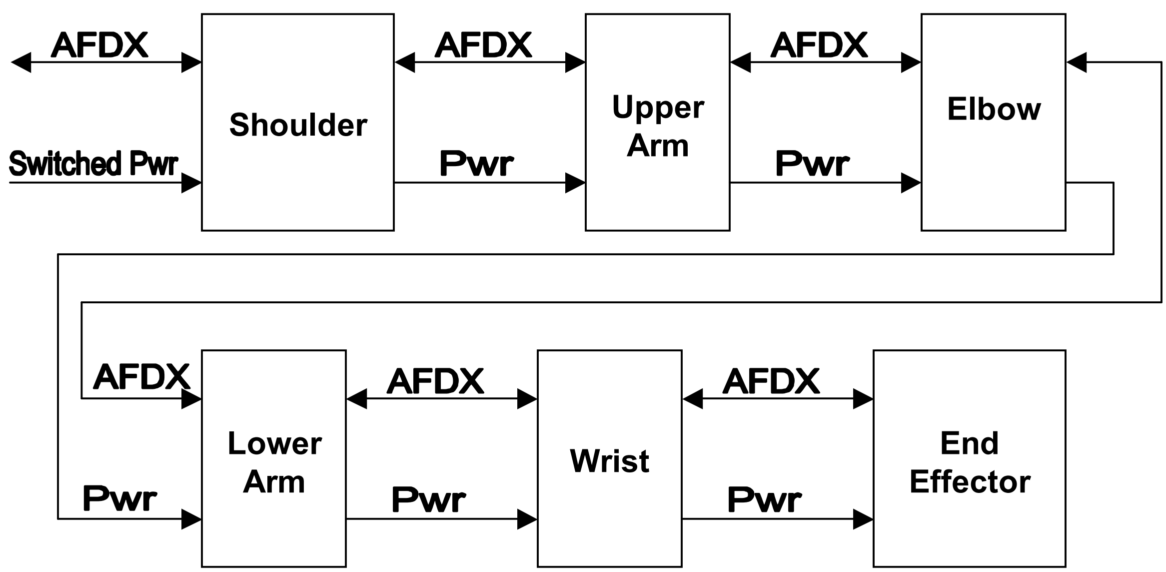

Figure 7: Remote Manipulator Arm Block Diagram

When the arm is in the "Stowed" position, all joint angles are at zero degrees except for the shoulder yaw which is at 180º. Positive angle movements correspond to: Pitch up, Yaw right, Roll right as viewed looking down the arm from the shoulder.

The RMA parts are physically connected in the following sequence:

a. Shoulder Yaw joint
b. Shoulder Pitch joint
c. Upper arm boom
d. Elbow joint
e. Lower arm boom
f. Wrist Pitch joint
g. Wrist Yaw joint
h. Wrist Roll joint
i. End Effector

The Upper arm, Lower arm, and Wrist all have cameras mounted on them. The AFDX address map for devices located in the RMA is given in Table 7.

Table 7: RMA AFDX Bus Address Map

Address	Receiver
0x400	Wrist Pitch Controller
0x410	Wrist Yaw Controller
0x420	Wrist Roll Controller
0x431	Camera Pitch Controller
0x432	Camera Yaw Controller
0x433	Camera Zoom Controller
0x434	Camera Lamp
0x435	Camera Image Sensor
0x770	Lower Arm Camera Controller
0x771	Camera Pitch Controller
0x772	Camera Yaw Controller
0x773	Camera Zoom Controller
0x774	Camera Lamp
0x775	Camera Image Sensor
0x776	Lower Arm Data Module (for strain gage data)
0x300	Elbow Pitch Controller
0x780	Upper Arm Camera Controller
0x781	Camera Pitch Controller
0x782	Camera Yaw Controller
0x783	Camera Zoom Controller
0x784	Camera Lamp
0x785	Camera Image Sensor
0x786	Upper Arm Data Module (for strain gage data)
0x200	Shoulder Pitch Controller
0x210	Shoulder Yaw Controller

There are three basic message types used by the RMS Computer to communicate with all AFDX devices:

a) **Query Status – All:** Requests the status of all AFDX devices;
b) **Query Response:** Requests data of a specific AFDX device;
c) **Execute Command:** Issues a command for a specific AFDX device to execute.

AFDX messages from the RMS Computer to the Motor Controllers take the form shown in Table 8.

Table 8: AFDX Data Packet from RMS Computer to Motor Controllers

Message Type	AFDX Dest. Addx	Src Addx Data[0]	Data Type Data[1]	Data Wd Data[2]
1 = Query Status - All	Unused	0x0000	Unused	Unused
2 = Query Response	Device Addx	0x0000	1 = Status 4 = Motor Velocity 5 = Motor Angle 6 = Joint Angle (degrees)	Unused
3 = Execute Command	Device Addx	0x0000	2 = Self Test	Unused
			4 = Motor Velocity (RPM)	16-bit Integer

The motor controllers respond to commands from the RMS Computer with a status update and/or command acknowledgement message in the format shown in Table 9.

Table 9: AFDX Data Packet from Motor Controller

Message Type	AFDX Dest. Addx	Src. Addx Data[0]	Data Type Data[1]	Status Wd Data[2]	Data Wd Data[3]	Data Wd Data[4]
1 = Query Status - All	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused
2 = Query Response	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused
			4 = Motor Velocity	16-bit status word	16-bit Integer	Unused
			5 = Motor Angle	16-bit status word	0x0000	Unused
			6 = Joint Angle (degrees)	16-bit status word	Joint Angle Integer	Joint Angle Fraction * 4096
3 = Execute Command	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused

3.5.4.1 RMA Shoulder

The RMA Shoulder part contains two joints. The first is the yaw joint allowing rotation of the entire arm assembly about this joint in the horizontal plane. Connected to the yaw joint is the shoulder pitch joint which rotates the RMA assembly in the vertical plane.

All joints within the RMA comprise the following basic elements:

a. DC Motor
b. Gear reduction
c. High speed shaft encoder
d. Low speed shaft encoder
e. Motor controller

Figure 8 provides a block diagram of the RMA Shoulder.

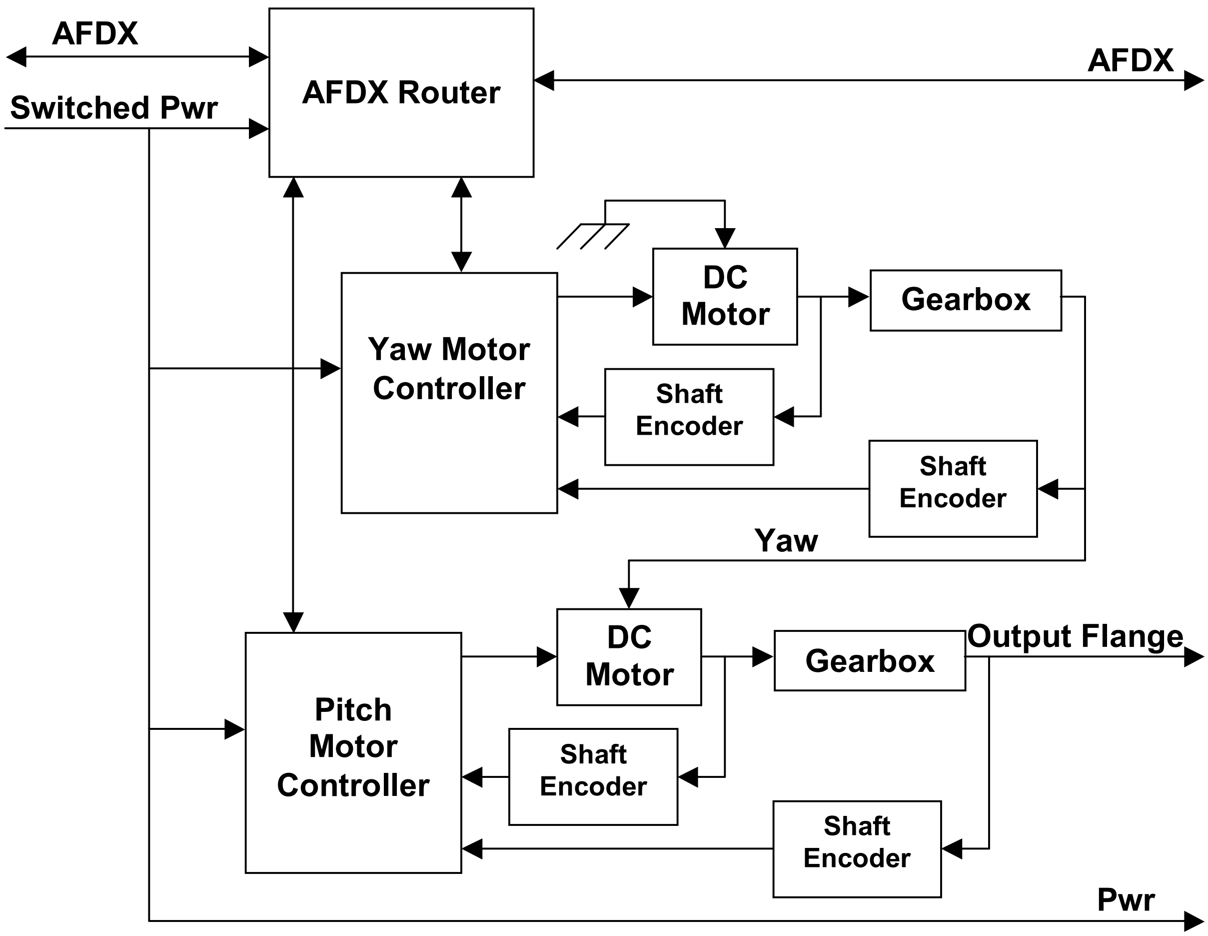

Figure 8: RMA Shoulder Block Diagram

The yaw motor is firmly fixed to the RMA shoulder mount flange that is attached to the shuttle bay port side longeron. The torque developed by the motor is amplified through a 500:1 planetary reduction gearbox whose output is connected to the shoulder pitch motor casing. The pitch motor output is connected to an identical gearbox whose output is connected to the RMA shoulder output flange. The shoulder output flange is in turn connected to the upper arm boom.

The motor controllers receive commands from the RMS Computer via the AFDX bus and convert them to the signals required for driving their respective joint motor. Shaft encoders attached to the motor output and gearbox output shafts provide positional and rate feedback for closed-loop operation by the motor controller. Motor controllers provide shaft angle, angular rate, and status data via the AFDX bus to the RMS Computer upon request.

3.5.4.2 RMA Upper Arm

The RMA Upper Arm is simply a 17-foot long boom that connects the shoulder to the elbow. The upper arm has a video camera mounted to it near the shoulder end and contains an AFDX router, a strain gauge, and a strain gage data converter module. A block diagram of the RMA Upper Arm is shown in Figure 9.

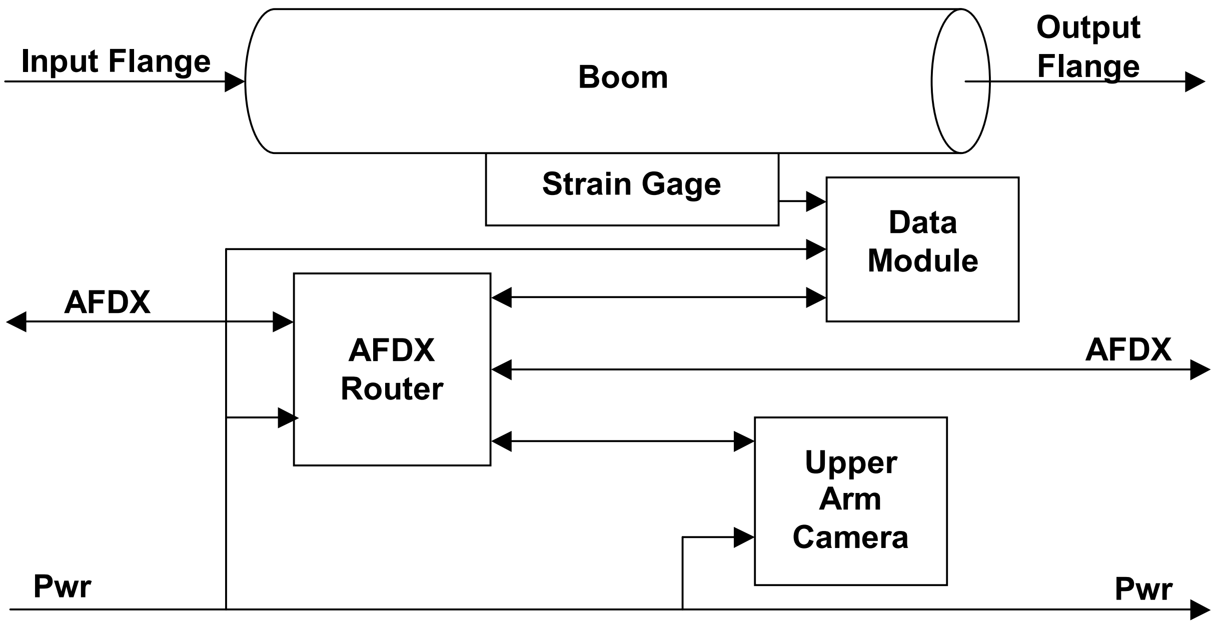

Figure 9: RMA Upper and Lower Arm Block Diagram

The Data Module is a four-channel analog data acquisition unit used to read the strain gauges and provide the interface to the AFDX bus. Table 10 and Table 11 list the AFDX command and response data formats used for communicating with the Data Module part. Command and data words are 32 bit integer values and the maximum amount of message data is 16 words.

Table 10: AFDX Messages from RMS Computer to Data Modules

Message Type	AFDX Dest. Addx	Src Addx Data[0]	Data Type Data[1]	Data Wd Data[2]
1 = Query Status - All	Unused	0x0000	Unused	Unused
2 = Query Response	Device Addx	0x0000	1 = Status	Unused
			7 = Resistance	0 = Ch. No. 0 1 = Ch. No. 1 2 = Ch. No. 2 3 = Ch. No. 3
3 = Execute Command	Device Addx	0x0000	2 = Self Test	Unused

The Data Module sends messages only in response to commands from a controlling device (e.g. RMS Computer). The format of the Data Module response messages is shown in Table 11. The Message Type field contains the code for the RMS Computer message for which the response has been generated.

Table 11: AFDX Messages from Data Module to the RMS Computer

Message Type	AFDX Dest. Addx	Src. Addx Data[0]	Data Type Data[1]	Status Wd Data[2]	Data Wd Data[3]	Data Wd Data[4]
1 = Query Status - All	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused
2 = Query Response	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused

Message Type	AFDX Dest. Addx	Src. Addx Data[0]	Data Type Data[1]	Status Wd Data[2]	Data Wd Data[3]	Data Wd Data[4]
			7 = Resistance	16-bit status word	0 = Ch. No. 0 1 = Ch. No. 1 2 = Ch. No. 2 3 = Ch. No. 3	Resistance (16-bit Integer)
			3 = Cmd Error	16-bit status word	Ch. No.	1 = Invalid Ch. No.
3 = Execute Command	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused

3.5.4.3 RMA Elbow

Figure 10 provides a block diagram of the RMA Elbow.

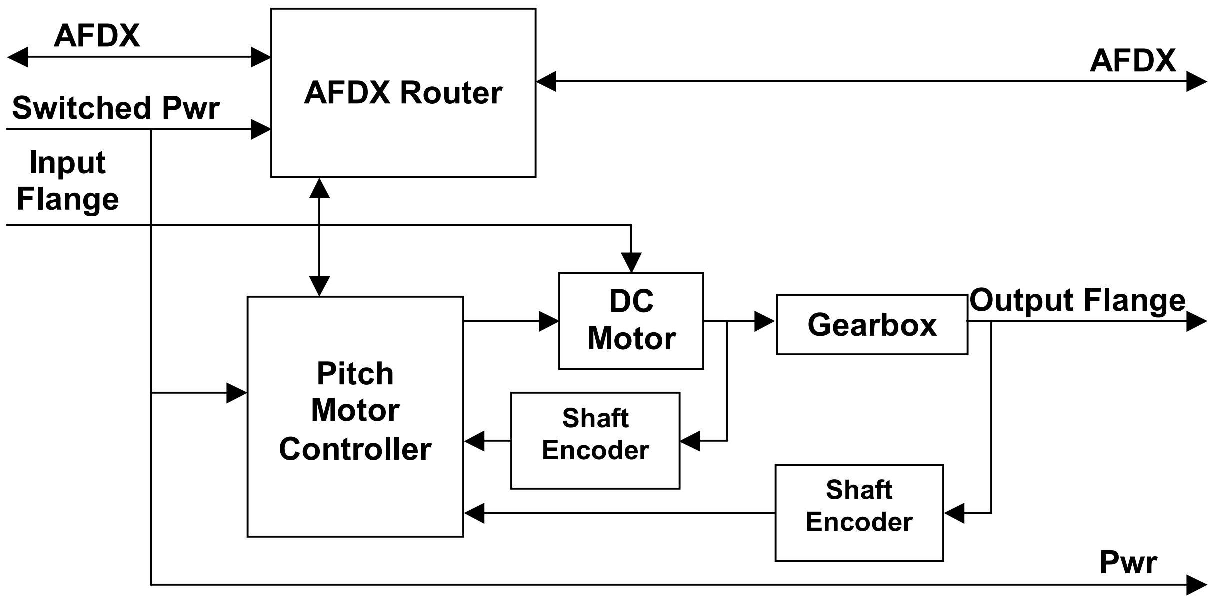

Figure 10: RMA Elbow Block Diagram

The RMA Elbow connects the upper arm and lower arm booms with a pitch joint. The elbow contains an AFDX router, a motor controller, a DC motor, a gearbox, and two shaft encoders.

The pitch motor is firmly fixed to the RMA upper arm boom elbow flange. The torque developed by the motor is amplified through a 500:1 planetary reduction gearbox whose output is connected to the elbow output flange. The elbow output flange is in turn connected to the lower arm boom.

The motor controller receives commands from the RMS Computer via the AFDX bus and converts them to the signals required for driving the joint motor. Shaft encoders attached to the motor output and gearbox output shafts provide positional and rate feedback for closed-loop operation by the motor controller. The motor controller provides shaft angle, angular rate, and status data via the AFDX bus to the RMS Computer upon request.

3.5.4.4 RMA Lower Arm

The RMA Upper Arm is simply a 20-foot long boom that connects the elbow to the wrist. As with the upper arm, the lower arm has a video camera mounted to it (only near the middle of the boom) and also contains an AFDX router, a strain gauge, and a strain gage data converter module. The block diagram of the RMA Lower Arm is identical to that of the RMA Upper Arm. Please refer to the diagram in Figure 9 for details.

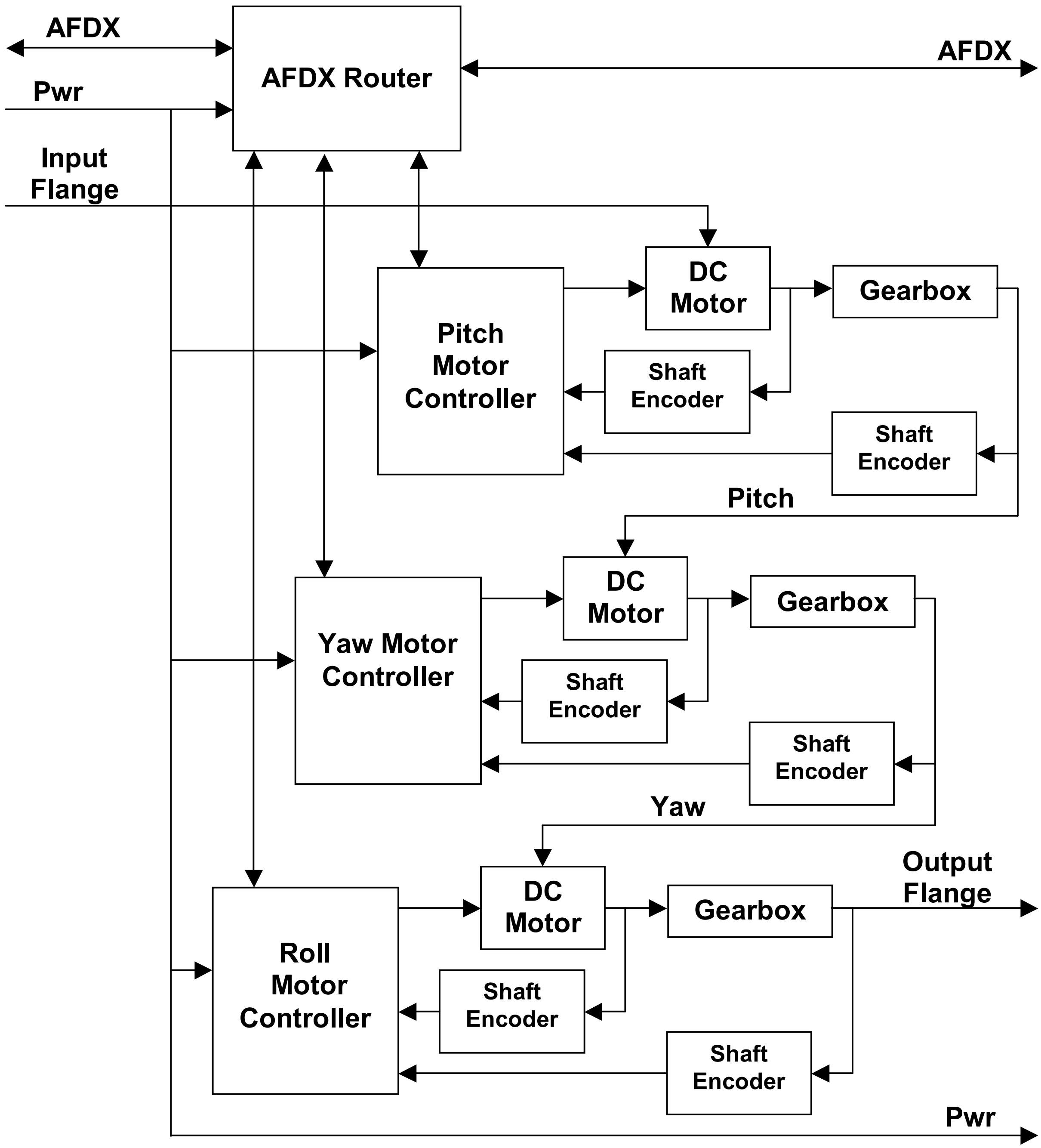

Figure 11: RMA Wrist Block Diagram

3.5.4.5 RMA Wrist

The RMA Wrist comprises three joints – pitch, yaw, and roll. The RMA Wrist connects the lower arm boom and the End Effector with a three-degree-of-freedom joint assembly. The wrist contains an AFDX router, a camera, and three of the following: a motor controller, a DC motor, a gearbox, and two shaft encoders. A block diagram of the RMA Wrist is shown in Figure 11.

The pitch motor is firmly fixed to the RMA lower arm boom output flange. The joints in the elbow operate exactly the same as those in the Shoulder. The wrist output flange is connected to the RMA End Effector.

3.5.4.6 RMA End Effector

The RMA End Effector provides the adapter between the RMA Wrist and the payload. The end effector does not have a functioning grapple, but is permanently affixed to the satellite payload for this project. The end effector could be enhanced with a functioning grapple for use on a future project.

3.6 Testability

The motor controllers are designed to report if the motor subsystem that it controls is not responding according to design. All of the motor controllers in the RMA and cameras are identical in this design and support the insertion and detection of faults for testing purposes. [SyRS: R25]

A set of tests has been designed to verify conformance to the functional characteristics specified herein and has been written to exercise the simulated SRMS. [SyRS: R26]

3.7 System constraints & safety considerations

Safety controls have not been implemented in the simulated SRMS.

4 System interfaces

Being essentially a self-contained system, the primary simulated SRMS system interface of interest is that through which the operator interacts. Interfaces through which the operator interacts with the SRMS are found on the RMS control & display panel (Figure 2), and are largely specified in section 3.4 and section 3.5 of this document. All remaining user interface features of the RMS control & display panel are specified in the as follows.

Six digital numeric indicators are provided on the RMS control & display panel to display the angle of each RMA joint in real-time. Additional data is displayed for each RMA joint indicating seek-angle, joint velocity, and joint fault status. [SyRS: R27]

A master Fault indicator is provided on the RMS control & display panel (Figure 2) that is illuminated when any SRMS subsystem reports a fault – including the RMA joint motor controllers. [SyRS: R28]

5 System testing

Refer to the System Test Design Document for information related to system testing.